Development of SITP's Large Capacity High Frequency Coaxial Pulse Tube Cryocoolers

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ABSTRACT

Large capacity high frequency single-stage coaxial inertance pulse tube cryocoolers have been developed and are becoming mature in SITP/CAS. The main objective of the development is to provide larger low-noise cooling powers in the range of 80-100 K for space-borne infrared detector systems. The design and performance optimization approaches are discussed, and the engineering models for them are in work. A split dual opposed piston linear compressor with a maximum swept volume of 8.2 cc is used, and the overall weight without cooler control electronics is below 7.0 kg. At present, the coolers have achieved over 12% of Carnot at 80 K, or 14% of Carnot at 100 K. The typical cooling performance of the coolers provides 5 W at 80 K or 8 W at 100 K with around 120 W of electric input power and a 313 K reject temperature. Approaches to further optimize the thermodynamic performance and detailed characterization tests are underway.

INTRODUCTION

Cryogenic infrared instruments are by far the largest application of space cryogenics, and the world's aerospace industry has been actively seeking means for multiyear cryogenic cooling in space to enable long-life infrared sensors since the 1950s.[1] Two types of regenerative cryocoolers, Stirling and pulse tube cryocoolers (PTC), have been researched in great depth and have played important roles in the practical applications to date.[2,3,4] Compared with Stirling, pulse tube cryocoolers offer two meaningful advantages: any wear-out at the cold end is eliminated, which results in higher reliability, and the vibration output level of cold fingers is significantly reduced due to the absence of a moving displacer.[5] Thus, for applications like space-borne infrared detector cooling, where MTTF, reliability and vibration are critical, PTC technology is becoming more and more attractive.

Research on high frequency PTCs has been an increasing focus at the Shanghai Institute of Technical Physics, Chinese Academy of Sciences (SITP/CAS) in recent years. The attractive merits of this technology—reliable cold fingers with low vibration output, low EMI levels, and potential for long lifetime—make PTCs a worthy research focus. At present our single-stage PTC prototypes cover the range from 30 K to 200 K, with typical cooling capacities from hundreds of milliwatts to tens of watts. This performance gives them the potential to provide effective cooling for HgCdTe-based InfraRed Focal Plane Arrays (IRFPA) covering wavelengths from near visible down to the Long Wave Infrared (LWIR) region.[6]

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Of all the types of PTCs developed or under development at SITP/CAS, the large-capacity types, which have the potential to provide larger cooling powers in the range of 80-100 K, have achieved the highest level of maturity. These PTCs are focused at providing high reliability, low-noise cooling for larger Short Wave (SW) and Medium Wave (MW) IRFPAs. At present, the experimental prototypes have already achieved very satisfactory cooling capacity and refrigeration efficiency. Some subtypes are progressing into the Engineering Model (EM) phase, and still others are undergoing rigorous acceptance, characterization and endurance testing based on customer requirements.

CRYOCOOLER DESIGN

Optimization of Dimensional Parameters

Our design and optimization principle is to maximize the COP and/or the cooling capacity of a coaxial PTC based on the requirements of the cold finger dimensions. A simplified computer simulation model and fast design method have been established for performance prediction and optimization.[7] The model is based on a finite difference method to solve the mass, energy, and momentum conservation equations, and some empirical coefficients have been added considering the multi-dimensional effects in practical pulse tubes. In the model, the geometrical and operating parameters are optimized simultaneously to acquire the maximum COP and/or cooling capacity.

The simulation is based on a split dual opposed piston linear compressor with a maximum swept volume of 8.2 cc, which is connected to the cold finger by a 30 cm flexible tube. Considering the working temperature and the capacity, 400-mesh stainless steel screens are used as the regenerator matrix. The average filling pressures vary from 3.0 MPa to 3.5 MPa. The simulations are based on the warm and cold temperature of 300 K and 80 K, respectively.

For a coaxial PTC, where the pulse tube is concentrically inserted into the regenerator, the outer diameter of the cold finger is often roughly fixed by the end application. For our applications, the defined requirements on the cold finger diameter are around 25 mm. As a result, the remaining values that can be selected during optimization include regenerator length, and pulse tube length and diameter. The following provides an example of the design process for determining the dimensional parameters.

Figure 1 shows the simulation results for the variation of COP and cooling capacity at 80 K with regenerator length. The corresponding compressor piston amplitude is around 3.85 mm to provide the corresponding required PV work, and the mean filling pressure is set at 3.2 MPa. Interestingly, as shown in Figure 1, the COP and cooling power change in different ways as the regenerator length is varied. Our goal is to find the optimum point for both, or at least an acceptable point for both. While giving consideration to both requirements, we selected 66 mm as the best compromise length.

Based on the same principle, Figures 2 and 3 give the simulation results of the variation of COP and capacity with pulse tube length and inner diameter, respectively. The appropriate length and inner diameter dimensions are then determined.

Optimization of the Phase Shifting Mechanism

After the PTC's dimensions are determined, its maximum refrigeration capacity is also nearly determined. The remaining work is focused on how to realize that performance. This is the function of the phase shifting mechanism. For certain applications, some phase-shifters, like the double-inlet, may bring instability to the performance and are not recommended. We choose an inertance tube accompanied by its associated gas reservoir as the only phase-shifters. Both simulations and experiments conducted in our laboratory show that for the mid-size PTCs, the phase shifts induced by the inertance tubes are appropriate and enough, which is quite different from the situation for the miniature coaxial PTCs we are developing. It should be pointed out that, for nearly all the PTC types we have developed, we have used two or three segments of

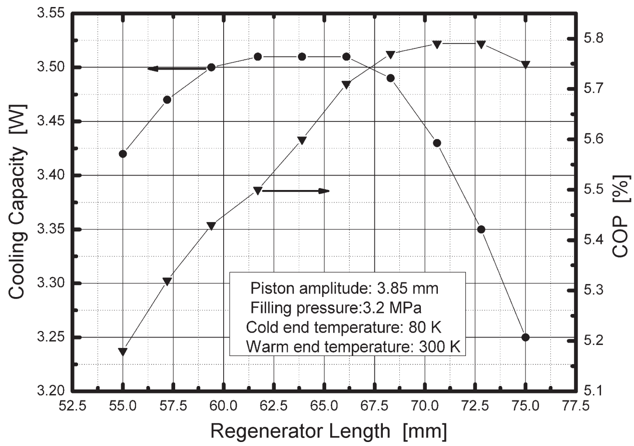

Figure 1. Simulation result of COP and cooling capacity at 80 K versus regenerator length.

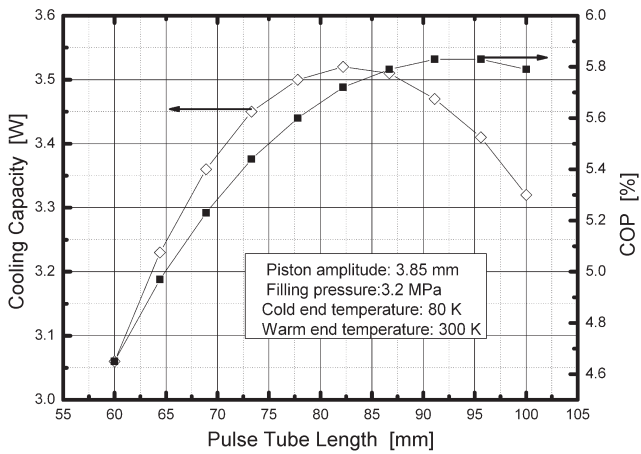

Figure 2. Simulation result of COP and cooling capacity at 80 K versus pulse tube length.

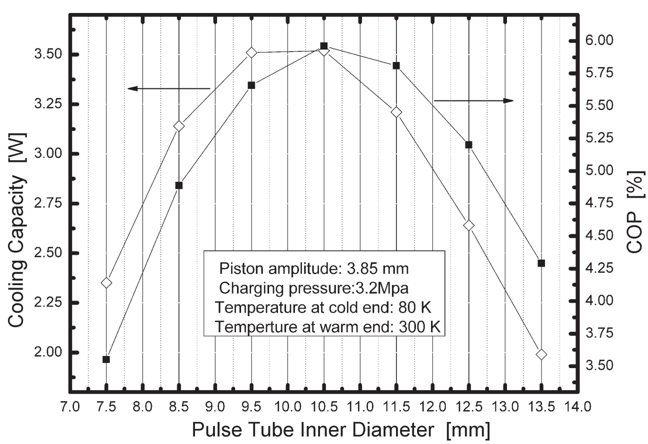

Figure 3. Simulation result of COP and cooling capacity at 80 K versus pulse tube inner diameter.

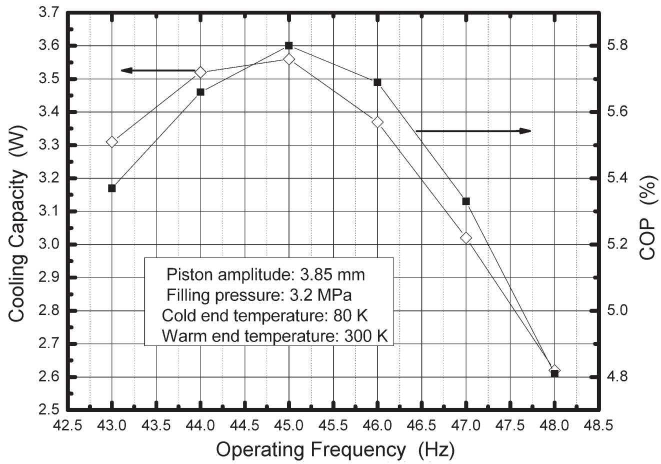

Figure 4. Simulation result of COP and cooling capacity at 80 K versus operating frequency.

inertance tubes with various inner diameters and lengths rather than a single section with a fixed inner diameter.

Optimization of the Operating Parameters

It should be pointed out that the dimensional and operating parameters are optimized altogether in the model. However, before the optimum dimensions are determined, the operating parameters are roughly estimated and may change in a wide range as the optimum dimensional parameters are defined. Therefore, after the final dimensions are fixed, the operating parameters need to be optimized again to adapt to the given dimensions. Figure 4 shows the optimization results on the operating frequency, and an optimum value of 45 Hz is chosen.

In the simulation for average filling pressure, a monotonic decrease of the no-load temperature has been observed from 3.0 to 7.0 MPa. However, the COP at 80 K changes very little from 4.0 to 7.0 MPa. For mechanical considerations and long-life operation, we finally chose 3.2 MPa as an appropriate average filling pressure, though the efficiency will be somewhat poorer than at 4.0 MPa.

VERIFICATION EXPERIMENTS

A series of large capacity coaxial PTCs operating in the 80-100 K temperature range have been fabricated based on the above design method. Figures 5 and 6 show some key components, and Figure 7 shows the experimental setup for investigating the cooler's thermodynamic performance.

Figure 8 shows typical cooldown curves, and Figure 9 gives typical cooling performance at 60 K, 80 K and 100 K for input electric powers of 80 W, 100 W and 120 W. The typical cooling capacity is 5.0W at 80 K with 121.3W of input electric power, and 8.0W at 100 K with 122.7 W of input electric power — all at a reject temperature of 313 K. We observe that the coolers have relatively poor refrigeration efficiencies at 60 K compared with our 60 K-version coolers. The main reason is due to the different design goals. The 60 K-version coolers usually can work fairly well at 80-100 K, but not verse visa.

It should be especially pointed out that the developed cooler prototypes can work very well with a high reject temperature. This is also one of our main design goals. At present, the reject temperature is set deliberately at 313K, or even higher, since the future applications require the cooler to operate smoothly over a wide fluctuating ambient temperature range, especially at high temperatures.

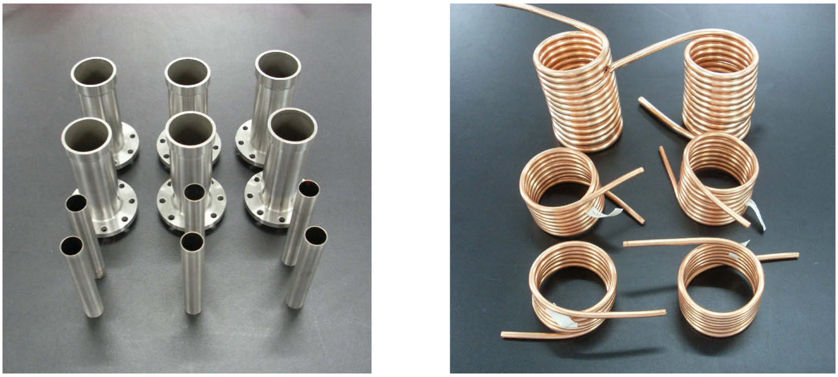

Figure 5. (Left) Regenerators and pulse tubes. (Right) Inertance tubes

Figure 6. (Left) Cold heads. (Right) Gas-inlet manifold structures.

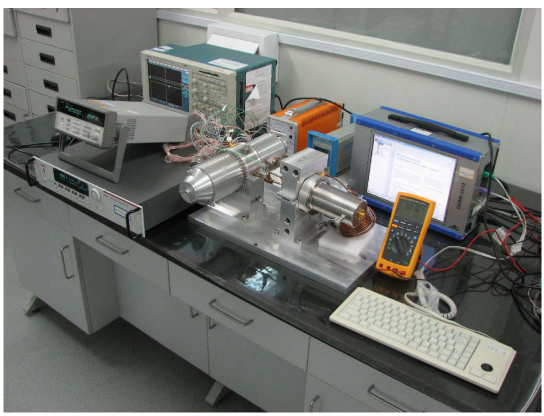

Figure 7. Experimental setup for investigating the cooler's thermodynamic performance.

ENGINEERING MODEL

Because the large capacity prototypes are relatively mature, Engineering Models (EMs) for them have been finalized for near-future applications.

Figure 10 (left) shows a CAD drawing of an EM cold head concept (the compressor is not displayed). It is an all-welded structure. The inertance tubes are completely inserted into the gas reservoir, and then the reservoir is welded to the warm heat exchanger. The cold heat exchanger is connected to the regenerator using laser weld technology. Figure 10 (right) shows a finished EM cooler (including the compressor).

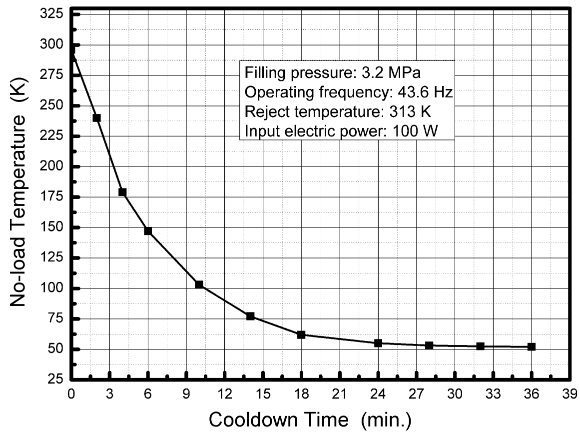

Figure 8. Cool down curves.

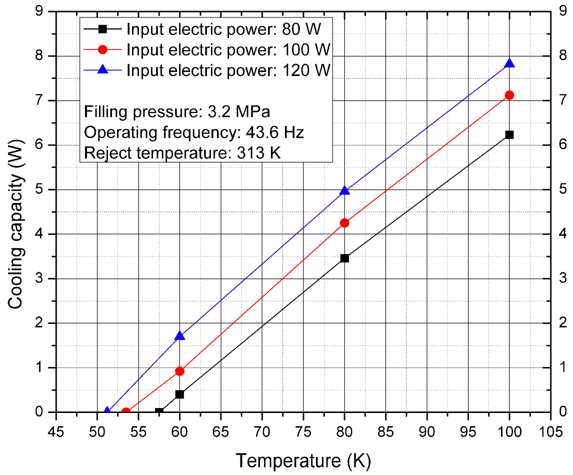

Figure 9. The experimental cooling performance.

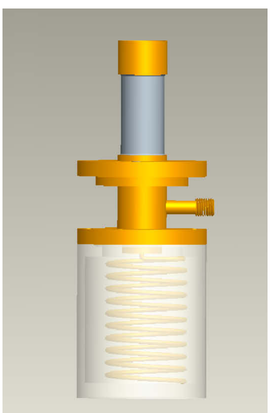

Figure 10. (Left) EM concept. (Right) Finished EM cooler with compressor

The overall weight of any EM version is controlled to below 7.0 kg (The cooler control electronics is not included). Preliminary tests show that the various EM units have nearly the same thermodynamic performance.

DISCUSSION AND CONCLUSIONS

SITP/CAS has developed a series of large-capacity high-frequency single-stage coaxial inertance pulse tube cryocoolers to provide low-noise cooling powers of a few watts in the range of 80-100 K for space-borne infrared detector systems. At present the design theory and fabrication processes are quite mature, and engineering models have been fabricated. For the typical cooler, the overall weight without cooler control electronics is below 7.0 kg. The coolers have achieved over 12% of Carnot at 80 K, or 14% of Carnot at 100 K. The typical cooling performance of the coolers provides 5 W at 80 K or 8 W at 100 K with around 120 W of electric input power and 313 K reject temperature. A variety of optimization approaches are underway to further enhance their thermodynamic performance, and detailed characterization tests are ongoing.

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